Lockheed Martin Space Mission Systems & Services
Science, Engineering, Analysis, and Test
2400 NASA Road 1, P.O. Box 58561, Houston, TX 77258-8561
Telephone (281) 333-5411

LOCKHEED MARTIN

September 21, 1999
Task Order 9HECECAYS
HDID-2G42-1167
LMSEAT 33214

TO: M. Ewert /EC2

VIA: A. Milliken /C70 *Original initialed by: AM*
J. Keener /C70 *Original initialed by: JFK*
K. Andish /C70 *Original initialed by: KA*

FROM: B. Gertner /C70 *Original initialed by: BG*

SUBJECT: Mars Greenhouse Study: Natural vs. Artificial Lighting

This paper discusses a preliminary study that compares artificial light to the natural lighting for growing crops on Mars. This study relates the amount of edible plant mass that would be grown to the amount of light available as:

$$\text{Edible} = 0.77 \cdot \text{PAR} - 6.1$$

where *Edible* is the of edible plant mass produced, g/(m$^2\cdot$ day), and *PAR* is the lighting level of photo-synthetically active radiation (PAR) in mol/(m$^2\cdot$ day) [1]. This equation defines the relationship between light and edible plant growth within this study. The assumption that the crew needs 0.97 kg food/(crew$\cdot$ day) was used with the above equation to calculate the area that is needed to grow enough food for a Martian year (686.5 Earth days). Assuming 6 crewmembers, the total amount of food needed in a Martian year is 3995.4 kg. By using the above correlation and the total amount of PAR for each scenario, the total growing area to provide the correct amount of food for each scenario was determined. With the area, all other assumptions (see Table 1- Assumptions and Values) were translated into mass, volume, power, and cooling [2]. Then, those numbers were translated into an equivalent systems mass (ESM) [2].

The three scenarios chosen were a rigid biomass production chamber (BPC), an inflatable greenhouse, and a hybrid greenhouse that utilized some artificial light. Some systems were not included in the ESM calculation. All air, water, solids, and similar systems were assumed to be the same for all scenarios. The thermal equipment was assumed to be the same in each scenario except for the equipment involved in cooling the lights and plant machinery. The plant nutrient system was assumed to be the same since the same amount of edible plant mass was grown. The differences in these three cases were the amount of lighting used, the amount of support structure and machinery used, and the equivalent volume of the various outer structures.

The level of available PAR depended upon whether natural lighting or artificial lighting was used. To determine the amount of natural lighting, some assumptions were made involving deep space radiation and what might happen as it passes through the Martian atmosphere [3]. Atmospheric conditions for nominal weather and local dust storms were calculated. That dust storms would prevail for the "winter" season was also assumed. With these assumptions, the average daily PAR on Mars was calculated as 20.8 mol/(m^2· day). The actual amount of daily PAR changes throughout the Martian seasons. This would cause a variance in the amount of edible biomass grown. One assumption was that food was stored during the year when excess was grown. For the times when natural lighting conditions worsened and did not allow the generation of enough food, the stored food made up the difference. When artificial lighting at 1000 μmol/(m^2· s) is used, there is 43 mol/(m^2· day) of PAR. When 400 μmol/(m^2· s) of artificial lighting is used, there is 17 mol/(m^2· day). Also, the lower the transmittance that can actually be achieved, the more comparable the hybrid system becomes to the natural greenhouse system. The higher the transmittance the more favorable the natural greenhouse system is over the other two systems. The assumed overall transmittance for the greenhouse in this study was 85%. The reduction from 100% transmittance is to account for structural interference and material for all natural lighting calculations.

The end result of this study was that the inflatable greenhouse using only natural lighting (ESM of 52 MT) was only marginally better than an inflatable hybrid system (ESM of 55 MT). Both performed better than a rigid BPC arrangement (ESM of 113 MT). {MT is a metric ton equivalent to a Mg.}

- The rigid BPC was much more massive than either the inflatable greenhouse or the hybrid system. The rigid BPC had a large ESM (113 MT) for two reasons. First, though the overall volume for a rigid BPC is considerably less than either of the other options, the mass per volume for the rigid structure at 66.7 kg/m^3 is significantly heavier than the inflatable structures at 2.07 kg/m^3. Second, the high power and cooling requirements associated with the completely artificial lighting also contributed to its high ESM.
- The power and cooling requirements for machinery accounted for most of the ESM (52 MT) associated with the inflatable greenhouse. The machinery power and secondary structure mass were significant because the growth area was triple that of the rigid BPC.
- The hybrid system had an ESM (55 MT) because it made use of natural lighting plus some artificial lighting. Using artificial light required a quantity of power, yet it was sufficient to reduce the area significantly. Still, this did not help reduce its mass below that of the inflatable greenhouse that used only natural lighting.

The results of this study depend heavily upon the assumptions made. The following items need further evaluation to test the ideas presented in the study:

- The lighting levels on Mars need to be measured to a greater accuracy, especially spectral distribution with regard to PAR for plant growth.
- The inflatable greenhouse concept needs further development, including all support structure and machinery needed to use the greenhouse.
- Plant growth at both low pressure and low light levels needs further investigation to accurately quantify yields.
- Investigations need to be performed to determine edible yields for specific crops at these varying conditions, and how transpiration and gas exchanges are affected.
- Any further analysis of this topic will need the full-time support and expertise of a horticultural scientist.

Table 1- Assumptions and Values

General		
Number of crew	6	Crew
Total Edible grown needed	0.97	kg/E day/crew
Total Edible grown needed	5.82	kg/E day
Duration	1	Mars yr
Duration	686.5	E day
Duration	668	Mar day
Martian Day	24.665	E hr
Duration	16476	E hr
Total Edible grown needed	3995.4	kg
Plants		
Edible=0.77*PAR -6.1		
	Edible	g/ m^2/E day
	PAR	mol/ m^2/E day
Note: Must have at least	200	µmol/ m^2/s
Greenhouse		
Transmittance Efficiency	0.85	
Average PAR	20.754	mol/ m^2/E day
PAR is a function of season		
BPC		
PAR if constant 1000 PPF	43	mol/ m^2/E day
Hybrid		
PAR if constant 400 PPF	17	mol/ m^2/E day
Transmittance Efficiency	0.85	
Average PAR	20.754	mol/m^2/E day
PAR is a function of season		
ESM Costs [2]		
Volume BPC (ISS module)	66.7	kg/m^3
Volume Inflatable	2.08	kg/m^3
Power	87	kg/kW
Cooling	66.7	kg/kW

Secondary structure and Machinery [2]		
Mass per Area	9.8	kg/ m^2
Volume per Area (Estimate)	0.5	m^3/ m^2
Power per Area (Estimate)	0.3	kW/ m^2
Cooling per Area (Estimate)	0.3	kW/ m^2
Lighting for 1000 µmol/ m^2/s [2]		
Lamp per Area	5.07	lamp/ m^2
Mass per Lamp	0.21	kg/lamp
Volume per Lamp	0.000625	m^3/lamp
Power per Lamp	0.4	kW/lamp
Cooling per Lamp	0.4	kW/lamp
Mass of cooling equipment	7.02	kg/m^2
Lighting for 400 µmol/ m^2/s		
Lamp per Area (0.4 times above)	2.028	lamp/m^2
Mass per Lamp	0.21	kg/lamp
Volume per Lamp	0.00625	m^3/lamp
Power per Lamp	0.4	kW/lamp
Cooling per Lamp	0.4	kW/lamp
Mass of cooling equipment (0.4 times above)	2.808	kg/m^2
Volume per growth Area		
BPC Length	11.3	m
BPC Diameter	4.572	m
BPC growth Area	82.4	m^2
BPC Volume	185.5	m^3
BPC Ratio	2.25	m^3/ m^2
Length of Greenhouse	15.0	m
Diameter of Greenhouse	7.6	m
Width of growing area (2m tall, 1m clearance)	4.46	m
Greenhouse growth Area (length *width)	66.9	m^2
Greenhouse Volume (Semi cylinder)	340.2	m^3
Greenhouse Ratio	5.08	m^3/ m^2

REFERENCES

1. Wheeler, R., *et al.* “NASA’s Biomass Production Chamber: A Testbed for Bioregenerative Life Support Studies.” Adv. Space Res., Vol. 18, No. 4/5, pp. 215-224, 1996.
2. Drysdale, A. and Hanford, A. “Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document.” JSC-39317 (CTSD-ADV-371), National Aeronautics and Space Administration, Johnson Space Center, Texas, June 1999.
3. Hanford, A., Lockheed Martin Space Operations, Houston, Texas. Personal Communications. September 1999.

DISTRIBUTION

Name	Copies	Mail Code
Ewert, M.		EC2
Tri, T.		EC3
Fortson, R.		EC3 /LM
Wheeler, R.		JJ-G /KSC
Drysdale, A.		KA91 F530
Jones, H.		SSR /ARC
Milliken, A.		C70
Keener, J.		C70
Andish, K.		C70
Hanford, A.		C70
Duffield, B.		C70
Gertner, B.	(2)	C70
Records Center	(2)	B15
T. O. File		